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CRITERIA OF THE LONGITUDINAL STABILITY OF THE EKRANOPLAN

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

GREEK ALPHABET

Alpha	Α	α	α		Nu	Ν	ν	
Beta	Β	β			Xi	Ξ	ξ	
Gamma	Γ	γ			Omicron	Ο	ο	
Delta	Δ	δ			Pi	Π	π	
Epsilon	Ε	ε	∊		Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ			Sigma	Σ	σ	ς
Eta	Η	η			Tau	Τ	τ	
Theta	Θ	θ	ϑ		Upsilon	Υ	υ	
Iota	Ι	ι			Phi	Φ	φ	ϕ
Kappa	Κ	ϰ	κ	ϰ	Chi	Χ	χ	
Lambda	Λ	λ			Psi	Ψ	ψ	
Mu	Μ	μ			Omega	Ω	ω	

CRITERIA OF THE LONGITUDINAL STABILITY OF THE EKRANOPLAN

R. D. Irodov

Examined are some questions of the longitudinal stability of the ekranoplan* directly connected with the selection of its aerodynamic design.

The ekranoplan is a flight vehicle which uses the effect of a considerable increase in the lift properties and lift-drag ratio of a wing in flight near the surface (screen). The favorable effect of the screen appears greater, the less the height of the location above it of the trailing edge of the wing expressed in parts of a chord. With the assigned wing area and the assigned absolute distance from the screen to the trailing edge of the wing, determined by the possible height of the uneveness of the screen, the effect of the screen will be greater, the less the wing aspect ratio. This fact defines the design of the ekranoplan as a flight vehicle with a low aspect-ratio wing [1]. Some features of the aerodynamic characteristics of the ekranoplan lead to the need for the introduction of new stability criteria and the appearance in connection with this of additional requirements

*Translator's Note. This term is a transliteration from the Russian and not listed in dictionaries; it is believed to be some kind of air-cushion vehicle which moves over the surface on an air cushion.

for its aerodynamic design.

1. The equations of pitching of the ekranoplan do not differ in form from similar equations for an aircraft and are written in the form [2]

$$\left.\begin{aligned} \frac{dV}{dt} &= g(n_x - \sin\theta), \\ \frac{d\theta}{dt} &= \frac{g}{V}(n_y - \cos\theta), \\ \frac{d^2\vartheta}{dt^2} &= \frac{M_z}{I_z}, \\ \frac{dH}{dt} &= V\sin\theta, \end{aligned}\right\} \qquad (1)$$

where g is the force of gravity [m/s^2],

n_x and n_y - ratio to the weight of the aircraft of the sum of projections of the thrust of the engines and aerodynamic forces on the horizontal and vertical axes of a high-speed coordinate system,

t - time [s],

V - flight speed [m/s],

θ - flight path angle [rad],

ϑ - pitch angle [rad],

H - flight altitude (distance from the center of gravity of the ekranoplan to the surface of the screen) [m],

M_z - pitching moment [kgf·m].

The weight of the ekranoplan G and its moment of inertia I_z in the analysis of motion during short time intervals can be considered to be constant. The effect of the aerodynamic forces on the ekranoplan is assigned by dependences n_x, n_y and M_z on the parameters which determine the flight conditions, taking into account the obvious equation of constraint $\vartheta=\theta+\alpha$, where α is the angle of attack.

When evaluating the stability of the aircraft, the dominant role is played by the examination of motion at a constant velocity

(short-period motion). Let us write the equations of the short-period motion of the ekranoplan in increments, being based on the same assumptions as those in the case of an aircraft [2]: V=const; $\theta=\theta_{исх}+\Delta\theta$; $n_y=n_{y\ исх}+\Delta n_y$; $H=H_{исх}+\Delta H$; $\vartheta=\vartheta_{исх}+\Delta\vartheta$; $M_z=M_{z\ исх}+\Delta M_z$.

The initial mode is the horizontal steady flight: $\theta_{исх}=0$; $M_{z\ исх}=0$; $n_{y\ исх}=1$.

As a result of these assumptions the first equation of system (1) becomes identical ($n_x\equiv 0$), and the other three are written in the form

$$\left.\begin{aligned} &\Delta\dot{\theta}=\frac{g}{V}\Delta n_y,\\ &\Delta\ddot{\alpha}+\Delta\ddot{\theta}=\frac{1}{I_z}\Delta M_z,\\ &\Delta\dot{H}=V\Delta\theta \end{aligned}\right\} \qquad (2)$$

(the dot denotes differentiation with respect to time).

Assuming further that the angles of attack α and the deviations of the stabilizer ϕ and flight altitude H in the process of the disturbed motion are changed within such limits, and that increases in the aerodynamic coefficients Δc_y and Δm_z $\left(\Delta n_y=\frac{\rho V^2}{2G}S\Delta c_y;\right.$ $\Delta M_z=\frac{\rho V^2}{2}Sb_A\Delta m_z$, where ρ is the air density [kg·s²/m⁴], b_A - the average aerodynamic chord of the wing [m], S - the wing area $\left.[m^2]\right)$ can be considered linearly dependent on them, let us write

$$\Delta c_y=c_y^{\alpha}\Delta\alpha+c_y^{H}\Delta H;$$
$$\Delta m_z=m_z^{\alpha}\Delta\alpha+m_z^{\dot{\alpha}}\Delta\dot{\alpha}+m_z^{\varphi}\Delta\varphi+m_z^{\omega_z}\omega_z+m_z^{H}\Delta H.$$

Here $\omega_z=\frac{d\vartheta}{dt}$ is the angular rate of rotation of the ekranoplan, ϕ is the angle of deflection of the stabilizer. After substituting the expressions for Δc_y and Δm_z into the system and after excluding

an increase in the flight path angle $\Delta\theta$, we will obtain the system of two linear differential second-order equations with constant coefficients.

Converting in this system to a new time unit τ_m, dependent on parameters of the ekranoplan and flight conditions $\tau = \frac{t}{\tau_m}$, $\tau_m = \frac{2G/S}{\rho g V}$ [s], introducing the differential operator with respect to the dimensionless time $D = d/d\tau$ and after designating for brevity

$$2\varkappa = c_y^{\alpha} - \frac{m_z^{\bar{\omega}_z} + m_z^{\dot{\bar{\alpha}}}}{i_z};$$

$$\omega_0^2 = -\frac{\mu}{i_z} c_y^{\alpha} \sigma_n; \quad \bar{\omega}_z = \omega_z \frac{b_A}{V};$$

$$\dot{\bar{\alpha}} = \frac{d\alpha}{dt} \frac{b_A}{V};$$

$$\bar{H} = \frac{H}{b_A};$$

$\mu = \frac{2G/S}{\rho g b_A}$ is the relative density of the ekranoplan;

$i_z = \frac{g}{G} \frac{I_z}{b_A^2}$ - dimensionless moment of inertia;

$\bar{x}_T - \bar{x}_{F\alpha} = \frac{m_z^{\alpha}}{c_y^{\alpha}}$ - reserve of the longitudinal static stability with respect to the angle of attack is the distance in parts of the MAC of the center of gravity of the ekranoplan ($\bar{x}_T$) up to the point of the application of a lift increment because of a change in the angle of attack $\bar{x}_{F\alpha}$;

$\bar{x}_T - \bar{x}_{F\bar{H}} = \frac{m_z^{\bar{H}}}{c_y^{\bar{H}}}$ - reserve of the longitudinal static stability with respect to the height above the screen is the distance in the fractions of the MAC from the center of gravity of the ekranoplan to the point of application of a lift increment because of a change in flight altitude ($\bar{x}_{F\bar{H}}$);

$\sigma_n = \bar{x}_T - \bar{x}_{F\alpha} + \frac{m_z^{\bar{\omega}_z}}{\mu}$ - reserve of the longitudinal static stability with respect to overload ($\bar{x}$, $\bar{x}_{F\alpha}$ and $\bar{x}_{F\bar{H}}$ by definition are positive with the location of the center of gravity and foci behind the leading

edge of the MAC of the wing), let us write the system of equations of the disturbed motion of the ekranoplan (2) in the following form convenient for analysis:

$$(D^2 + 2\xi D + \omega_0^2)\Delta\alpha + \left[c_y^{\bar{H}} D - \frac{\mu}{i_z} c_y^{\bar{H}}\left(\bar{x}_T - \bar{x}_{F\bar{H}} + \frac{m_z^{\bar{\omega}_z}}{\mu}\right)\right]\Delta\bar{H} = \frac{\mu}{i_z} m_z^{\varphi}\Delta\varphi(\tau);$$

$$\mu c_y^{\alpha}\Delta\alpha - (D^2 - \mu c_y^{\bar{H}})\Delta\bar{H} = 0.$$

In the absence of the effect of the screen, i.e., the effect of the flight altitude on aerodynamic coefficients ($c_y^{\Pi} = m_z^{H} = 0$), this system falls into two independent equations: the equation of the short-period motion

$$(D^2 + 2\xi D + \omega_0^2)\Delta\alpha = \frac{\mu}{i_z} m_z^{\varphi}\Delta\varphi(\tau)$$

and the equation which describes a change in the altitude depending on the change in the angle of attack,

$$D^2\Delta\bar{H} = \mu c_y^{\alpha}\Delta\alpha(\tau), \text{ i.e., } \Delta\bar{H} = \mu c_y^{\alpha}\int_0^{\tau}\left(\int_0^{\tau}\Delta\alpha(\tau)\,d\tau\right)d\tau,$$

or the equations which describe a change in the angle of attack and flight altitude in the short-period motion,

$$(D^2 + 2\xi D + \omega_0^2)\Delta\alpha = \frac{\mu}{i_z} m_z^{\varphi}\Delta\varphi(\tau),$$

$$(D^2 + 2\xi D + \omega_0^2)D^2\Delta\bar{H} = \frac{\mu^2}{i_z} c_y^{\alpha} m_z^{\varphi}\Delta\varphi(\tau).$$

With $2\xi>0$ and $\omega_0^2>0$ in the isotropic atmosphere at constant velocity, the aircraft is stable with respect to angle of attack and is neutral in flight altitude. Consequently, for the precise maintaining of constant altitude of the flight, there must either be the pilot's virtually continuous interference in the aircraft control or the introduction of stabilization of the aircraft with

respect to the altitude by the means of automatic control.

With flight near the screen (i.e., the earth's surface or water) the forces and moments which act on the aircraft depend substantially not only on the angle of attack but also on the altitude. Therefore, the system which describes the motion of the ekranoplan at constant velocity does not break up into two independent second-order equations. By eliminating an increase in the angle of attack from the system, it is possible to write one equation of the fourth order, which describes a change in the flight altitude of the ekranoplan in the short-period motion

$$\left[D^4 + 2\xi D^3 + (\omega_0^2 - \mu c_y^{\bar{H}})D^2 - \mu c_y^{\bar{H}}(2\xi - c_y^{\alpha})D + \frac{\mu^2}{i_z} c_y^{\alpha} c_y^{\bar{H}}(\bar{x}_{F\bar{H}} - \bar{x}_{F\alpha})\right]\Delta\bar{H} = \frac{\mu^2}{i_z} c_y^{\alpha} m_z^{\varphi} \Delta\varphi(\tau).$$

Similarly it is possible to write the equation which describes a change in the angle of attack of the ekranoplan:

$$\left[D^4 + 2\xi D^3 + (\omega_0^2 - \mu c_y^{\bar{H}})D^2 - \mu c_y^{\bar{H}}(2\xi - c_y^{\alpha})D + \frac{\mu^2}{i_z} c_y^{\alpha} c_y^{\bar{H}}(\bar{x}_{F\bar{H}} - \bar{x}_{F\alpha})\right]\Delta\alpha = \frac{\mu}{i_z}(D^2 - \mu c_y^{\bar{H}}) m_z^{\varphi} \Delta\varphi(\tau).$$

2. Let us write the characteristic equation of the system in the standard form:

$$D^4 + A_1 D^3 + A_2 D^2 + A_3 D + A_4 = 0,$$

where

$$A_1 = 2\xi = c_y^{\alpha} - \frac{m_z^{\dot{\alpha}} + m_z^{\bar{\omega}_z}}{i_z};$$

$$A_2 = \omega_0^2 - \mu c_y^{\bar{H}} = -\frac{\mu}{i_z} c_y^{\alpha}\left(\sigma_n + i_z \frac{c_y^{\bar{H}}}{c_y^{\alpha}}\right);$$

$$A_3 = -\mu c_y^{\bar{H}}(2k - c_y^{\alpha}) - \frac{\mu}{i_z} c_y^{\bar{H}}(m_z^{\dot{\alpha}} + m_z^{\bar{\omega}_z});$$

$$A_4 = \frac{\mu^2}{i_z} c_y^{\bar{H}} c_y^{\alpha} (\bar{x}_{F\bar{H}} - \bar{x}_{F\alpha}) = -\frac{\mu^2 D(c_y, m_z)}{i_z D(\alpha, \bar{H})}.$$

where $\frac{D(c_y, m_z)}{D(\alpha, \bar{H})}$ is the Jacobian functions $c_y(\alpha, \bar{H})$ and $m_z(\alpha, \bar{H})$.

The stability of motion in the case of the equation of the fourth order will be provided for with

$$A_1, A_2, A_3, A_4 > 0 \text{ and } A_1 A_2 A_3 - A_1^2 A_4 - A_3^2 > 0.$$

For all the aircraft designs in the field of flight angles of attack, inequality $c_y^{\alpha} > 0$ is fulfilled. The conditions of the stabilization of ekranoplan outside the effect of the screen is the fulfillment of inequality $\sigma_H < 0$.

From tests of profiles, wings and layouts of aircraft near the screen, it is known that usually the lift coefficient at the assigned angle of attack is increased with the approach toward the screen (Fig. 1), i.e., $c_y^{\bar{H}} < 0$.

From equations for the calculation of coefficients of A_1, it is evident that under these assumptions conditions $A_1 > 0$, $A_2 > 0$ and $A_3 > 0$ are always satisfied. Consequently, the stability conditions of the short-period motion of the ekranoplan with flight near the screen are reduced to two inequalities: $A_4 > 0$ and $A_1 A_2 A_3 - A_1^2 A_4 - A_3^2 > 0$.

The satisfaction of the first condition ensures the aperiodic stability of the ekranoplan (i.e., the absence of the nonnegative real roots of the characteristic equation), and the satisfaction of the second condition ensures its oscillatory stability (i.e., the absence of the nonnegative real parts of the complex roots of the characteristic equation).

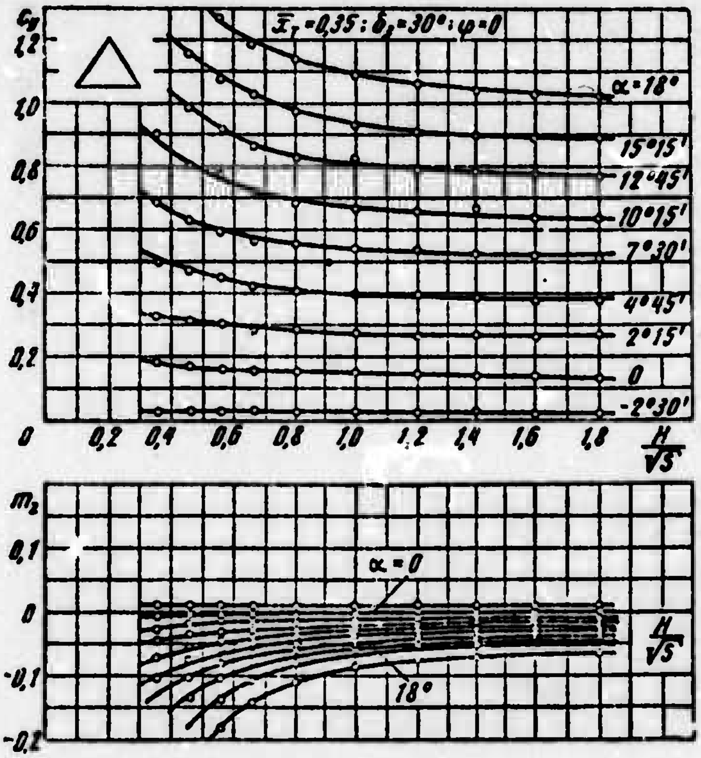

Figure 1

After substituting the expressions which determine the coefficients in terms of arodynamic derivatives, it is possible to write the stability criteria of the ekranoplan in the short-period motion in the following form:

aperiodic stability -

$$\bar{x}_{F\bar{H}} - \bar{x}_{F\alpha} < 0 \qquad (3)$$

or, at any sign by derivative $c_y^{\bar{H}}$,

$$\frac{D(c_y;\, m_z)}{D(\alpha;\, \bar{H})} < 0; \qquad (3a)$$

oscillatory stability -

$$\bar{x}_T - \frac{1 - \frac{c_y^{\dot{\alpha}}}{2\varkappa}\frac{\bar{x}_{F\alpha}}{\bar{x}_{F\bar{H}}}}{1 - \frac{c_y^{\dot{\alpha}}}{2\varkappa}}\bar{x}_{F\bar{H}} + \left(\frac{c_y^{\bar{H}}}{2\varkappa} i_z + \frac{m_z^{\bar{\omega}_z}}{\mu}\right) < 0. \qquad (4)$$

Thus in order to insure the aperiodic stability of the ekranoplan, it is necessary by the selection of the aerodynamic layout to insure the position of the focus in altitude above the screen ($\bar{x}_{F\bar{H}}$) in front of the focus with respect to the angle of attack ($\bar{x}_{F\alpha}$). To provide for oscillatory stability, it is necessary to select centering $\bar{x}_T$ in an appropriate manner.

Consequently, unlike the aircraft the longitudinal static stability of which in the absence of the compressibility effect of the air, with any aerodynamic layout, can always be provided

for by the selection of centering, the longitudinal aperodic (static) stability of the ekranoplan under these conditions can be provided for only with a definite form to the selected aerodynamic layout. If the aerodynamic layout of the ekranoplan is such that the focus in altitude above the screen is placed behind the focus with respect to the angle of attack, then by the selection of the center-of-gravity location the aperiodic stability of the ekranoplan cannot be insured.

In model tests with a screen in wind tunnels understood by the height of the model above the screen usually is the distance from the screen to the trailing edge of the wing at the place of its intersection with the mean aerodynamic chord.

Under conditions of considerable dependence of the aerodynamic characteristics of the ekranoplan on flight altitude, the derivatives c_y^α and m_z^α and the focus for the angle of attack $\bar{x}_{F\alpha}$ prove to be dependent on the point with respect to which there occurs the rotation of the ekranoplan with a change in the angle of attack. The focus in altitude $\bar{x}_{F\bar{H}}$ does not depend on the position on the MAC of this point. If values c_y^α, m_z^α and $\bar{x}_{F\alpha}$, determined with the rotation of the ekranoplan relative to the trailing edge of the wing, are assigned, then their values with the rotation of the ekranoplan relative to the center of gravity can be calculated according to the equations

$$(c_y^\alpha)_{\text{т}} = (c_y^\alpha)_{\text{з.к}} - c_y^{\bar{H}}(1 - \bar{x}_{\text{т}});$$

$$m^\alpha_{z\,\text{т}} = m^\alpha_{z\,\text{з.к}} - m_z^{\bar{H}}(1 - \bar{x}_{\text{т}});$$

$$\bar{x}_{F\alpha\,\text{т}} = \bar{x}_{F\alpha\,\text{з.к}} \frac{1 - \dfrac{c_y^{\bar{H}}}{c^\alpha_{y\,\text{з.к}}}(1 - \bar{x}_{\text{т}})\dfrac{\bar{x}_{F\bar{H}}}{\bar{x}_{F\alpha\,\text{з.к}}}}{1 - \dfrac{c_y^{\bar{H}}}{c^\alpha_{y\,\text{з.к}}}(1 - \bar{x}_{\text{т}})}$$

(in the calculation of the derivatives $m_{z\ \text{з.н}}^{\alpha}$ and $m_z^{\bar{H}}$ the moment is measured relative to the center of gravity of the ekranoplan $\bar{x}_T$, and therefore both derivatives depend on the centering).

It is obvious that with the center-of-gravity displacement of the ekranoplan forward chordwise, its focus with respect to the angle of attack is displaced to the side of the focus in altitude above the screen and in the limit coincides with it with $\bar{x}_T \to -\infty$. Thus, the use for evaluation of the static longitudinal stability of the ekranoplan of data of model tests in wind tunnels in which the angle of attack was changed with the rotation of the model relative to the trailing edge of the wing cannot lead to an inaccurate qualitative evaluation - the order of location of the foci on the MAC of the wing does not depend on the center of rotation of the wing with a change in the angle of attack, i.e., on the centering of the ekranoplan.

The account of velocity change in the examination of the disturbed motion of the ekranoplan virtually does not change the condition of the aperiodic stability - the maximum rear centering, determined not allowing for a change in the flight speed, is somewhat displaced back in comparison with the actual, and with sufficiently forward centering the ekranoplan again loses oscillatory stability.

3. Let us consider for an example the longitudinal static (aperiodic) stability in flight near the screen of a delta-wing airplane, which has an elevator unit on its fuselage, the aerodynamic characteristics of which were given in Fig. 1. Figure 2 gives these characteristics reconstructed into the dependence $m_z(c_y)$ with $\bar{H}$=const and α=const (H - distance from the center of gravity of the model to the screen). The slope tangents of these curves are the reserves of stability in angle of attack $m_z^{c_y(\alpha)} = \bar{x}_T - \bar{x}_{F\alpha}$ and in height of the flight above the screen

$m_z^{c_y(\bar{H})} = \bar{x}_T - \bar{x}_{F\bar{H}}$, respectively, with the centering $\bar{x}_T = 0.35$. It is evident that at all the heights within limits of the effect of the screen and at all angles of attack the negative slope of the curve α=const is more than the slope of the curve $\bar{H}$=const: this means that the focus in angle of attack of the aircraft is located in front of the focus in height, which indicates the aperiodic instability of the aircraft with flight near the screen.

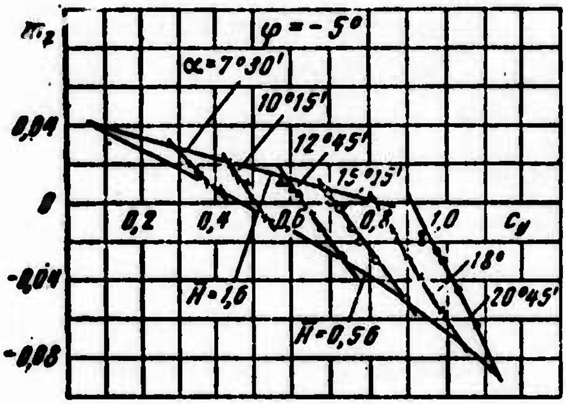

Figure 2

Taking into account that the focus in angle of attack of wings of small aspect ratios with the approach toward the screen only very insignificantly is displaced back so that the isolated wing can be considered neutral in height above the screen or weakly unstable, the considerable instability of the aircraft of a normal configuration with the low-positioned elevator unit can be explained by the fact that with the setting of the elevator unit in the lower position the focus in height above the screen is shifted back more than is the focus in angle of attack.

The setting of the fin on fuselage in front of wing (canard configuration), obviously, will lead to a shift in the focus in angle of attack forward and virtually will not change the position of focus in height above the screen, since the fin will undergo considerably less ground effect, since it lies above the wing at positive angles of attack, and its area is considerably less than the wing area. Hence it follows that the aircraft designed in a canard configuration will also be aperiodically unstable in flight near the screen.

Thus, the ekranoplan for providing longitudinal static

stability in flight near the screen must have a special aerodynamic design distinct from designs characteristic for aircraft with a low aspect-ratio wing.

One of the possible aerodynamic designs of the ekranoplan, proposed by Lippish [1], has highly positioned elevator unit. Such a fin shifts the focus in angle-of attack considerably more than does the focus in height above the screen, since it is located in a zone of a sufficiently weak effect of the screen (at least at sufficiently small angles of attack). This design ensures the position of focus in angle of attack behind focus in height above the screen under conditions of the maximum lift-drag ratio.

Another configuration can be "bob-tailed" with overflow in the root part (aircraft of "Dragon" J-35 type). With the approach toward the screen the overlow insignificantly changes the position of the focus in angle of attack ($\bar{x}_{F\alpha}$) but noticeably shifts forward the focus in the height of the flight ($\bar{x}_{F\bar{H}}$) because of a decrease in the relative distance from the screen of the wing center section with overflow in front.

4. For the practical problems of the evaluation of the static stability of the ekranoplan based on materials of tests of its model in a wind tunnel, it proves to be possible to write the condition of the aperiodic longitudinal stability of the ekranoplan (3a) in another form, which makes it possible to make evaluations according to only one derivative defined as the slope of the experimental curve, virtually without the additional reconstruction of curves obtained as a result of model tests. The main inequality

$$\frac{D(c_y,\ m_z)}{D(\alpha,\ \bar{H})}<0$$

can be written in any of the following four forms:

$$\left.\frac{dc_y}{d\alpha}\right|_{m_z=0} m_z^{\bar{H}}<0;\qquad \left.\frac{dc_y}{d\bar{H}}\right|_{m_z=0} m_z^{\alpha}>0;$$

$$\left.\frac{dm_z}{d\alpha}\right|_{c_y=c_{y\,\text{г.п}}} c_y^{\bar{H}}<0;\qquad \left.\frac{dm_z}{d\bar{H}}\right|_{c_y=c_{y\,\text{г.п}}} c_y^{\alpha}<0$$

(here $c_{y\,\text{г.п}}$ is the coefficient of lift in a horizontal steady flight). It is most convenient to use one of the last two inequalities. Since under cruising conditions of the flight $c_y^{\bar{H}}<0$, and $c_y^{\alpha}>0$, the stability criteria can be written in the form

$$\left.\frac{dm_z}{d\alpha}\right|_{c_y=c_{y\,\text{г.п}}}<0;\qquad \left.\frac{dm_z}{d\bar{H}}\right|_{c_y=c_{y\,\text{г.п}}}<0.$$

With $m_z^{\alpha}<0$ criterion $\left.\frac{dc_y}{d\bar{H}}\right|_{m_z=0}<0$ can be used. The derivatives can be found as slopes of curves of $m_z(\alpha)$ at c_y=const, $m_z(\bar{H})$ with c_y=const or $c_y(\bar{H})$ with $m_z=0$, as is shown on Figs. 3-5.

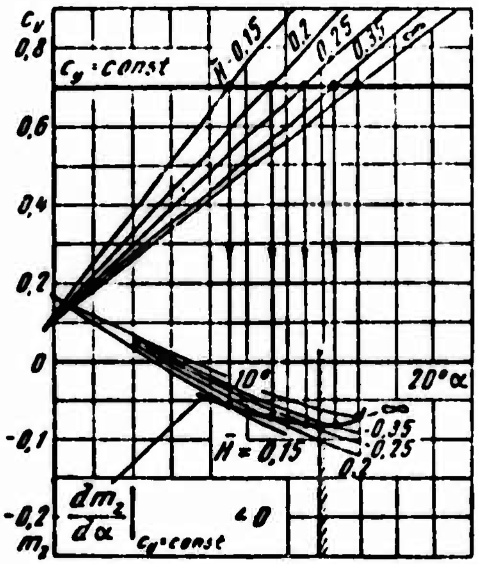

Figure 3

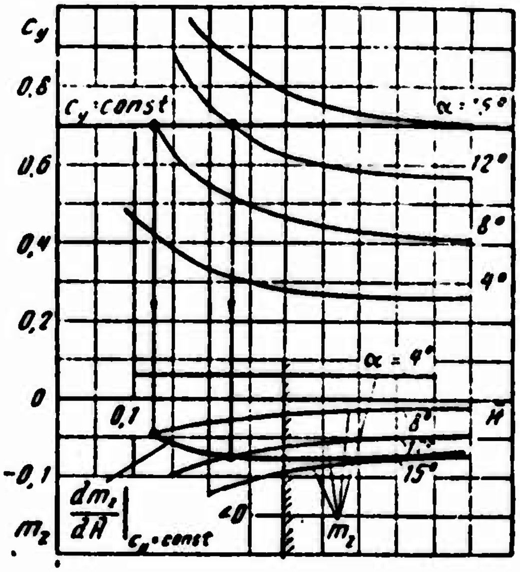

Figure 4

Since the stability of the ekranoplan is estimated under conditions of steady flight, the examination of stability, strictly speaking, makes sense only with $m_z=0$, i.e., at points of balancing.

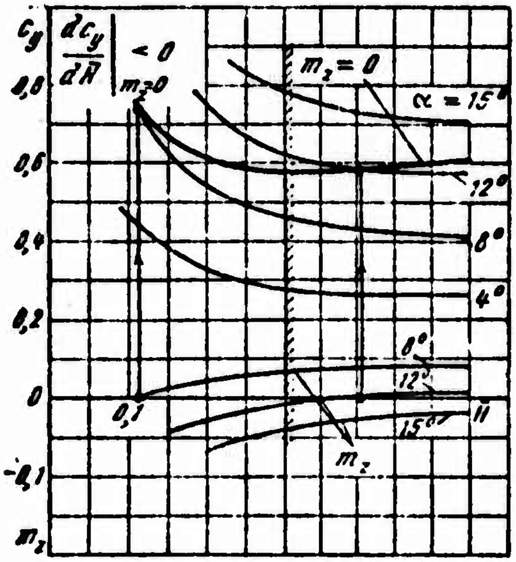

Figure 5

In the analysis of the stability of the aircraft, usually the assumption is made that the control-surface deflection does not change the position of focus in angle of attack, or, in other words, the slope of the curves $m_z(\alpha)$. Accepting this assumption for the ekranoplan and assuming additionally that the control deflection does not change the position of the focus in height above the screen, we obtain the possibility of judging the stability in slope of the appropriate curve $m_z(\alpha)$ or $m_z(H)$ with $c_y = c_{y\ r.p}$ and the arbitrary value of the pitching moment.

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